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Psychoacoustic Analysis of Synthesized Jet Noise

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ABSTRACT

An aircraft noise synthesis capability is being developed so the annoyance caused by proposed aircraft can be assessed during the design stage. To make synthesized signals as realistic as possible, high fidelity simulation is required for source (e.g., engine noise, airframe noise), propagation and receiver effects. This psychoacoustic study tests whether the jet noise component of synthesized aircraft engine noise can be made more realistic using a low frequency oscillator (LFO) technique to simulate fluctuations in level observed in recordings. Jet noise predictions are commonly made in the frequency domain based on models of time-averaged empirical data. The synthesis process involves conversion of the frequency domain prediction into an audible pressure time history. However, because the predictions are time-invariant, the synthesized sound lacks fluctuations observed in recordings. Such fluctuations are hypothesized to be perceptually important. To introduce time-varying characteristics into jet noise synthesis, a method has been developed that modulates measured or predicted 1/3-octave band levels with a (<20Hz) LFO. The LFO characteristics are determined through analysis of laboratory jet noise recordings. For the aft emission angle, results indicate that signals synthesized using a generic LFO are perceived as more similar to recordings than those using no LFO, and signals synthesized with an angle-specific LFO are more similar to recordings than those synthesized with a generic LFO.

1. INTRODUCTION

This study focuses on improving the realism of synthesized aircraft flyover noise presented in laboratory studies. Aircraft flyover noise is highly complex. The realism of synthesized aircraft flyover noise therefore depends on several factors including the effectiveness of synthesis methods used to generate individual noise sources (e.g., jet noise, fan noise) as well as incorporation of propagation and listener effects. A previous study explored the effectiveness of synthesis methods used to develop realistic fan noise via psychoacoustic testing.[1, 2] It was found that inclusion of fluctuations in amplitude and frequency enhanced realism under certain conditions. The present study focuses on the effectiveness of a new synthesis method for broadband jet noise. This new jet noise synthesis method was developed as part of a larger effort to create virtual environments for testing human response to aircraft flyover noise.[3-5]

Broadband jet noise may be synthesized in the time domain via a computationally intensive direct numerical simulation,[6] or more commonly from semi-empirical one-third octave band predictions. In the latter technique, predictions are typically based on time-averaged spectra, and therefore lack temporal variations observed in experimental data. The temporal variations of each one-third octave band may be characterized as low-frequency oscillations (LFO), each with

frequency content less than 20 Hz.[7] The jet noise synthesis method employed in this study may utilize either measured or predicted spectra for the mean one-third octave band level, modifying that level with empirically derived LFOs about the mean. Pressure time histories suitable for playback are synthesized by passing white noise through filters derived from those time-varying spectra.[3, 4] Since comparisons between synthesized and recorded data are to be made, the mean spectra used in this work were determined from the recordings in order to eliminate spectral differences which inevitably result between experimental data and predictions. Three different LFO types were considered over a range of emission angles (forward, mid, and aft). For the "specific-LFO" type, the mean data and the LFO data were acquired at the same emission angle. For the "generic-LFO" type, the mean data and the LFO data were acquired at different emission angles. In this case, the LFO data was acquired at a fourth emission angle between the mid and aft angles. Finally, for the "no-LFO" type, only the mean data was used.

The effectiveness of using different LFO types to create more realistic synthesized jet noise segments was evaluated via psychoacoustic testing. For this purpose, the two-alternative forced choice (2AFC) method was used. As part of the 2AFC method, subjects were first presented a reference signal (R) followed by two test sounds (A, B). Subjects were then asked to select the test sound more similar to the reference signal. The sample results were compared to a result based on chance alone (50%) to address the following research questions:

Q1. Can subjects distinguish between recordings and jet noise synthesized with no LFO applied to the mean spectra?
Q2. Can subjects distinguish between recordings and jet noise synthesized with a generic set of measured LFOs applied to the mean spectra?
Q3. Can subjects distinguish between recordings and jet noise synthesized with a specific set of measured LFOs applied to the mean spectra?
Q4. Do subjects find signals synthesized using specific LFOs more similar to recordings at that emission angle than signals synthesized using generic LFOs?
Q5. Do subjects find signals synthesized using generic LFOs more similar to recordings at that emission angle than signals synthesized with no LFOs?
Q6. Can subjects distinguish between jet noise synthesized with a generic set of measured LFOs, and jet noise synthesized with no LFOs?
Q7. Do results from Q1-6 vary with emission angles?
Q8. When R, A, and B, are all non-overlapping sections from the same recording, do subjects indeed choose A and B with approximately 50% probability?

2. METHODOLOGY

A. Setting and set-up

The psychoacoustic test was conducted in the Exterior Effects Room, a quiet acoustically-treated auditorium at the NASA Langley Research Center. Test signals were delivered to subjects over headphones, which were found to provide a consistent and nominally flat frequency response (not shown). Subjective responses were collected via tablet-PCs.

B. Subjects

A total of 30 subjects participated in the study in groups of five. Subjects were prescreened to ensure hearing loss no greater than 40 dB HL at 500-6000 Hz. A hearing specialist conducted hearing screening before and after the study to ensure that subjects' hearing was not affected by the test. Tests were conducted over the course of five consecutive weekdays.

C. Psychoacoustic test method

The psychoacoustic test method used was two-alternative-forced-choice (2AFC). Subjects were presented 21 different triads of jet noise. Each triad was composed of three 6-second signals including a reference signal (R) and two test signals (A,B). These three test sounds were presented consecutively with a 1-second pause between them (R-1s-A-1s-B). This sequence was repeated after a 2-second pause (R-1s-A-1s-B-2s-R-1s-A-1s-B). Subjects were provided a graphic on their tablet-PC display screen, which was updated to indicate the current signal being played. When the full sequence was completed, subjects were asked the question "Please tell us which of the following is more similar to R?" and instructed to select either the button labeled "A" or the one labeled "B". Eighteen of the 21 comparisons were presented twice; once forward (RAB) and once in reverse (RBA) to eliminate the potential bias due to presentation order. Three of the 21 comparisons were presented only once. These three "baseline" triads were each composed of nominally identical noise segments randomly selected from a longer recording. Overall, subjects were presented 39 triads of jet noise in three sessions of 13 signals. An equal number of comparisons with similar characteristics (i.e., emission angle, RAB/RBA order, and triad type) were assigned to each test session. The order of triads presented in each session was randomized for each group of five subjects. Finally, the presentation order of test sessions was also systematically varied across different subject groups via Latin-squares application.[8]

1. Configuration of triads

The triads tested are shown in Table 1. Each of seven triad types was tested at three emission angles. For each of the triad types, a score that is not significantly different from 50% implies that subjects, on average, did not find either test sound (A) or (B) more similar to the reference. The "no-LFO" triads (IDs 1-8-15) forced subjects to decide which of the following test sounds were more similar to the recording: (A) a non-overlapping segment of the same recordings, or (B) a sound synthesized with no LFO. This triad was used to address research question Q1. The "generic-LFO" triads (IDs 2-9-16) forced subjects to decide which of the following test sounds were more similar to the recording: (A) a non-overlapping segment of the same recording, or (B) a sound synthesized with a generic-LFO. This triad was used to address research question Q2. The "specific-LFO" triads (IDs 3-10-17) forced subjects to decide which of the following test sounds were more similar to the recording: (A) a non-overlapping segment of the same recording, or (B) a synthesized sound with a specific-LFO. This triad was used to address research question Q3.

The "specific-LFO vs. generic-LFO" triads (IDs 4-11-18) forced subjects to decide which of the following test sounds were more similar to the recording: (A) a sound synthesized with a specific-LFO, or (B) a sound synthesized with a generic-LFO. This triad was used to address research question Q4. The "generic vs. no-LFO" triads (IDs 5-12-19) forced subjects to decide which of the following test sounds were more similar to the recording: (A) a sound synthesized with a generic-LFO, or (B) a sound synthesized with no LFO. This triad was used to address research question Q5. The "generic vs. generic vs. no-LFO" triads (IDs 6-13-20) forced subjects to decide which of the following test sounds were more similar to the sound synthesized with a generic-LFO: (A) a sound synthesized with a generic-LFO, (B) a sound synthesized with no LFO. This triad was used to address research question Q6.

Also shown in Table 1 are the three "baseline" triads (IDs 7-14-21), which forced subjects to decide which of the following test sounds were more similar to the recording: (A) a non-overlapping segment of the same recording, or (B) a different non-overlapping segment of the same recording. A score not significantly different from 50% implies that subjects, on average, found neither test sound more similar to the reference. To validate the effectiveness of the two-

alternative-forced choice and confirm unbiased subjective responses (research question Q8), the sample proportion choosing (A) for the baseline triads is not expected to differ from chance (50%).

D. Test signal preparation and characteristics

1. Recordings

All jet noise recordings utilized in this study were collected in the Low Speed Aeroacoustic Wind Tunnel (LSAWT) at the NASA Langley Jet Noise Laboratory. The recordings were made using a linear array of microphones along a line parallel to the axis of a 1/10 scale engine exhaust nozzle model. The microphones were located outside the shear layer.[7] Data from four microphone locations were used in this study. Data for the forward emission angle were collected using the forward-most microphone, located 28.77º ahead of the center of the jet exit exhaust plane. Data for the mid and aft emission angles were collected using microphones at 19.97º and 65.39º behind the center of the jet exit exhaust plane, respectively. Data used for the "generic" LFO corresponding to an emission angle different than the above were acquired at an aft emission angle of 39.17º. Detailed information about emission angle coordinates can be found in Table 2 of reference [7].

Data were acquired at a sampling rate of 150k samples/second. Since a 1/10 scale model was used, this is equivalent to 15k samples/second full scale. The full scale record length of about 33 seconds was resampled to an audio sampling rate of 44.1k samples/second for playback to the test subjects.

Data were analyzed to determine the time-averaged one-third octave band spectra and LFOs for each emission angle, according to the method described in reference [7]. Time-averaged spectra were generated at one-third octave bands ranging from 20 Hz – 6.3 kHz, and are shown in Figure 1 for the three emission angles. The data have been normalized to a reference distance 3.52 m from the source, but no adjustments were made to account for absorption of sound in air. From the figure, it is clear that the aft recording is dominated by low frequency noise, while the mid and forward emission angle recordings are more broadband in character. The noise component of interest in this work is jet noise, which is dominant over other component sources at the aft angles under high power conditions. Therefore, the analysis focus is on the aft angle.

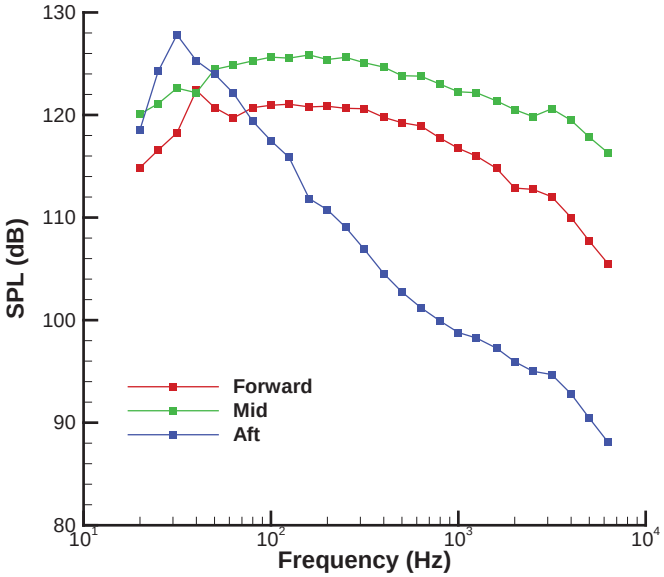

Figure 1. One-third octave band jet noise spectra for the three emission angles considered.

The time-varying characteristics of the jet noise data are shown in the spectrograms of Figure 2. It is clear that the temporal variations are of greatest amplitude in the aft emission angle. Hence, it is expected that changes in variations will be most perceptible at this angle. Low-frequency oscillations of each one-third octave band level over the full record length were obtained by subtracting the mean value from the total time-varying spectra. The spectral analysis was performed in such a way that time-varying fluctuations up to 20 Hz could be resolved.[7] A limit of 20 Hz is commonly used in synthesis because modulation above this frequency may be perceived as tones.

From this data, long segments of broadband jet noise were synthesized according to the aforementioned procedure at an audio sampling rate of 44.1k samples/second.

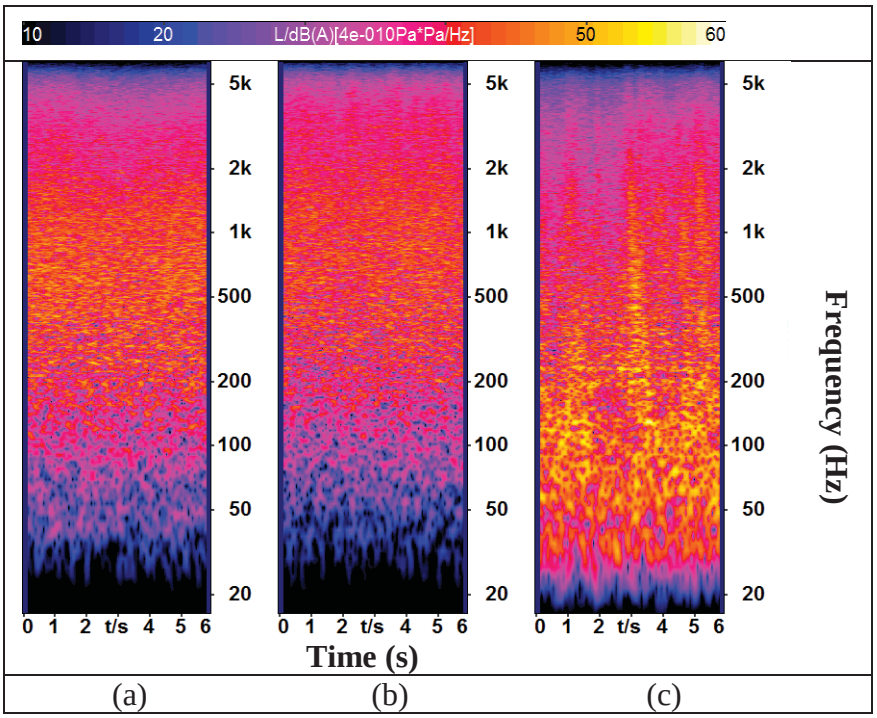

Figure 2. Spectrograms showing the nature of time-varying fluctuations observed in recorded jet noise segments at (a) forward, (b) mid, and (c) aft emission angles.

2. Preparation of test signals

Random 6-second-long segments of jet noise were extracted from the full length recorded and synthesized signals. The reference and test sounds used in a given triad were non-overlapping in time to encourage subjects to listen to the sounds in their entirety instead of taking cues from the specific features of a particular segment. For example, the reference and test sound (A) for ID 1 (see Table 1) were taken from non-overlapping segments of the forward recording. Each 6-second signal was band-pass filtered between 17.8 Hz and 5623 Hz using an 8-pole Butterworth filter. The operation was performed using the zero-phase "filtfilt" command in MATLAB. The low frequency cut-off was set to match the lower limit of the 20 Hz one-third octave band, below which the spectral content of the synthesized signal was virtually zero. The high-frequency cut-off was determined via informal listening tests. There it was found that using an 8-pole filter with a high-frequency cut-off of 5623 Hz was necessary to prevent subjects from taking cues from bandwidth differences between the recordings (7.5 kHz) and synthesized signals (7.08 kHz).

Following bandwidth adjustment, the signals were imported into HEAD Analyzer ArtemiS V12 sound quality software for further processing. The waveforms were scaled to the same loudness level of 40 sones (ANSI S3.4-2007[9]; FFT size: 32768; overlap: 50%) to eliminate loudness cues between test signals. A 0.05-second tapering window was applied at the beginning and end of each scaled signal to avoid clicks and pops during playback. The reproduced loudness levels during test were slightly different from 40 sones due to the gain associated with the reproduction system. However this gain was applied uniformly to all signals.

3. Temporal analysis of test signals

Spectrograms of non-overlapping segments of the variants of synthesized jet noise are next compared with spectrograms obtained from recordings. The forward, mid and aft emission angles are shown in Figure 3 – Figure 5, respectively. Differences between synthesized variants and recordings in the forward emission angle are barely distinguishable (see Figure 3), while those for the mid-emission angle are even less so (see Figure 4). At the aft emission angle shown in Figure 5, the signal containing specific-LFOs (d) is more visually similar to the recording (a) than the other synthesized jet noise segments, i.e., with no-LFO (b) or with a generic-LFO (c). Therefore, the spectrograms suggest that differences among synthesis variants will be more apparent at the aft emission angle than at other angles.

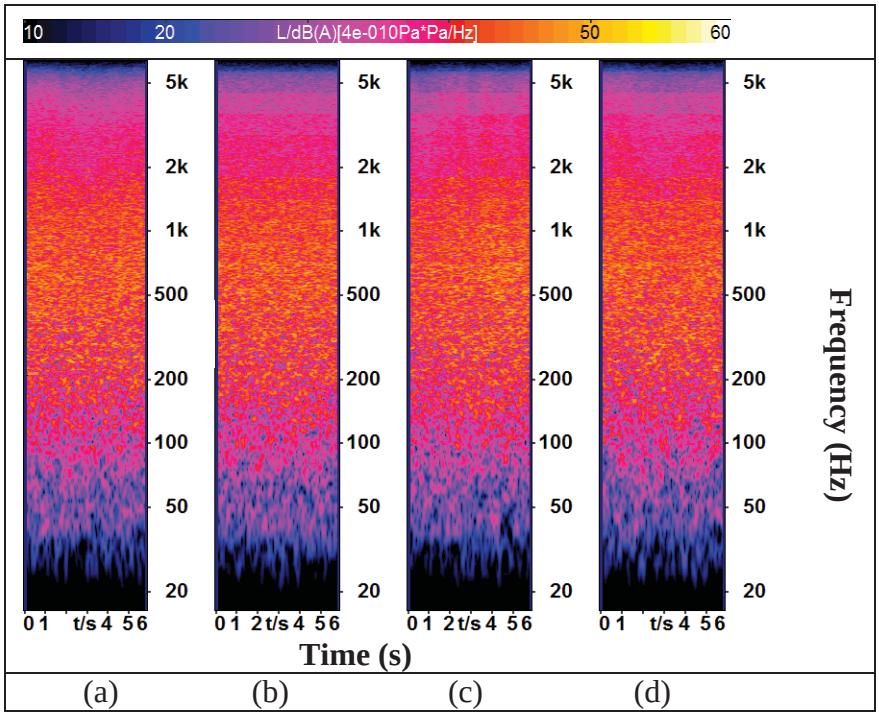

Figure 3. Spectrograms showing the nature of time-varying fluctuations observed in (a) recorded and synthesized jet noise segments at the forward emission angle for (b) no-LFO, (c) generic-LFO, (d) specific-LFO.

3. SUBJECTIVE DATA ANALYSIS

Each row in Table 1 displays the proportion of subjects that consider test sound (A) more similar to the reference sound (R) than (B). Binomial tests were conducted to assess whether the proportion choosing (A) differs significantly from chance (50%) by using the "Binomdist" function in Excel. The associated *p*-value is the probability of a result as high, or higher than, the sample proportion choosing (A) if subjects were supplying answers randomly, or by chance. Therefore, a *p*-value less than 'X' indicates a significant result at the 'X' level. Based on feedback obtained after testing, subjects found it much easier to perform the task during

sequences based on the aft emission angle than sequences based on either forward or mid emission angles. This is not surprising given the similarity of the spectrograms shown in Figure 3 and Figure 4. For this reason, analysis results were considered significant at the 10% level instead of the more standard 5% level.

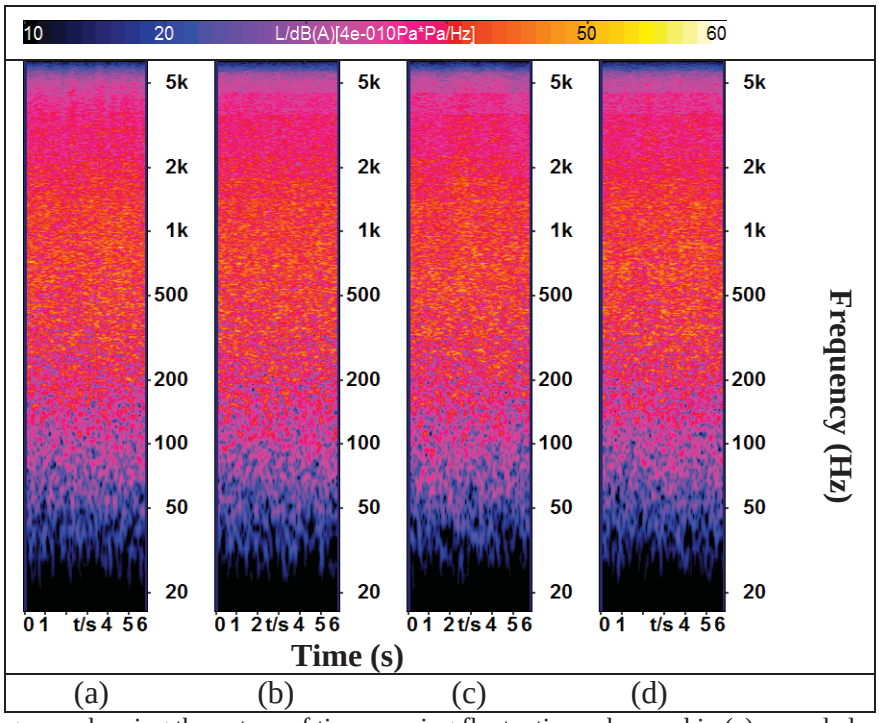

Figure 4. Spectrograms showing the nature of time-varying fluctuations observed in (a) recorded and synthesized jet noise segments at the mid emission angle for (b) no-LFO, (c) generic-LFO, (d) specific-LFO.

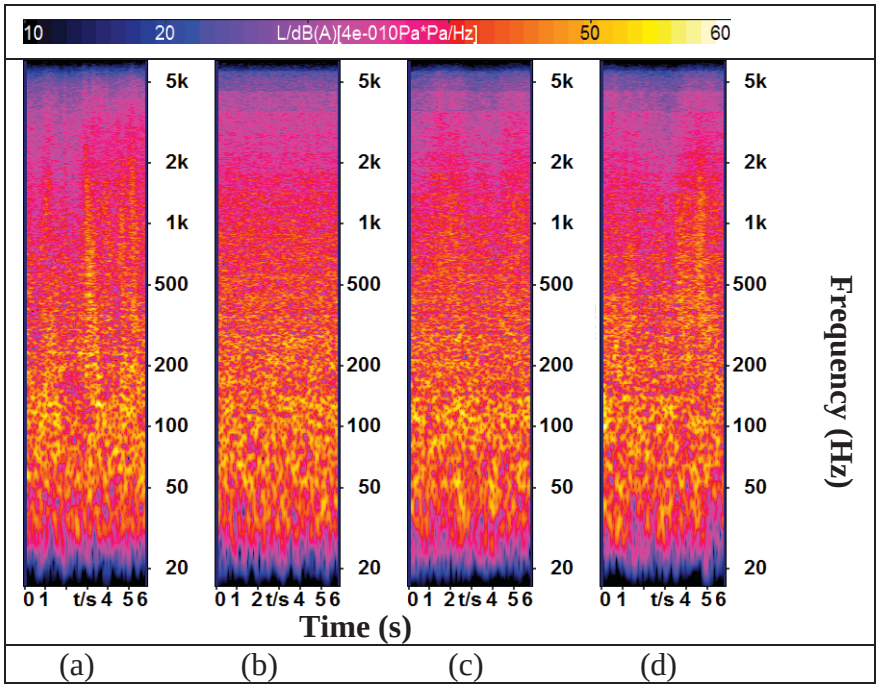

Figure 5. Spectrograms showing the nature of time-varying fluctuations observed in (a) recorded and synthesized jet noise segments at the aft emission angle for (b) no-LFO, (c) generic-LFO, (d) specific-LFO.

Table 1. Summary of preliminary subjective analysis results.

Emission angle	ID	Research question	Reference sound (R)	Test sound (A)	Test sound (B)	Responses choosing (A) (out of 30 or 60)	*p*-value
Forward	1	Q1	REC	REC	NO	27/60	0.740
	2	Q2	REC	REC	GEN	38/60	**0.014***
	3	Q3	REC	REC	SPEC	37/60	**0.026***
	4	Q4	REC	SPEC	GEN	40/60	**0.003***
	5	Q5	REC	GEN	NO	28/60	0.651
	6	Q6	GEN	GEN	NO	33/60	0.183
	7	Q8	REC	REC	REC	16/30	0.292
Mid	8	Q1	REC	REC	NO	23/60	0.954
	9	Q2	REC	REC	GEN	36/60	**0.060***
	10	Q3	REC	REC	SPEC	38/60	**0.046***
	11	Q4	REC	SPEC	GEN	35/60	**0.077***
	12	Q5	REC	GEN	NO	32/60	0.259
	13	Q6	GEN	GEN	NO	32/60	0.259
	14	Q8	REC	REC	REC	18/30	0.100
Aft	15	Q1	REC	REC	NO	42/60	**<0.001***
	16	Q2	REC	REC	GEN	44/60	**<0.001***
	17	Q3	REC	REC	SPEC	40/60	**0.003***
	18	Q4	REC	SPEC	GEN	43/60	**<0.001***
	19	Q5	REC	GEN	NO	35/60	**0.077***
	20	Q6	GEN	GEN	NO	28/60	0.650
	21	Q8	REC	REC	REC	16/30	0.292

* One-tailed binomial test result is significant at 0.10 confidence level.

Although 30 subjects were tested, the total number of responses for each non-baseline comparison includes both presentation orders RAB and RBA, so the sample size N is 60. For each baseline comparison (IDs 7-14-21), N is 30 since baseline triads were presented only once (RAB).

First, results regarding baseline comparisons (IDs 7-14-21) were analyzed to assess the reliability of 2AFC psychophysical method (research question Q8). The baseline comparisons were composed of three nominally identical non-overlapping segments randomly selected from a longer recording. Therefore, subjects' tendency to select (A) or (B) is not expected to differ from 50%. This expectation was supported by the test results, which show no evidence that subjective responses differ from chance (p=0.292, p=0.100, p=0.292).

Second, results for research question Q1-Q6 were analyzed for the aft emission angle. Based on results for ID 15 (research question Q1), subjects were able to distinguish between recordings and synthesized segments with no-LFOs (p<0.001). One explanation for this finding is that time-varying fluctuations were strong in the aft recordings, shown in Figure 5a, creating a stark subjective contrast with the segments synthesized with no-LFO, shown in Figure 5b. Subjects were also able to distinguish between recordings and both generic (p<0.001) and specific-LFO (p=0.003) synthesized segments, as shown for IDs 16-17 (research question Q2 & Q3). The result for ID 18 (research question Q4) indicates, notably, that subjects found segments synthesized with a specific-LFO to be more similar to recordings than segments synthesized with a generic-LFO (p<0.001). Furthermore, subjects found that segments synthesized with a generic-LFO were more similar to recordings than those synthesized with no-LFO (p=0.077), see ID 19 (research question Q5). These two results together seem to indicate the following ordering of synthesis techniques from least realistic to most realistic: no-LFO, generic-LFO, specific-LFO. Finally, there is no evidence that subjects could distinguish segments synthesized with a generic-LFO from those synthesized with no-LFO (p=0.65), as indicated for ID 20 (research question Q6).

Results for research question Q1-Q6 were also analyzed for the forward and mid emission angles. Findings were consistent with results from the aft emission angle, except in one case: there is no evidence that subjects could distinguish between recordings and synthesized segments with no-LFO (p>0.1). The reason for this finding is unknown. As part of the future investigations, more subjective and objective data analyses will be conducted to explore potential reasons. As a practical matter however, this result is of little consequence since other aircraft noise sources, e.g. forward radiated fan noise and airframe noise, dominate at these angles.

4. CONCLUSIONS

A psychoacoustic study was conducted to determine the effectiveness of a broadband synthesis method for jet noise. The study used the two-alternative-forced-choice method. Two variations of low frequency oscillations, generic and specific, were employed to investigate the realism of synthesized signals at varying levels of sophistication. A third variation using no-LFO was considered to represent the conventional synthesis approach. In the dominant aft region, the findings indicate that synthesis using a generic-LFO is more similar to recordings than synthesis using no-LFO. Further, synthesis using a specific-LFO was found to be more similar to recordings than synthesis using a generic-LFO. Results were similar at the forward and mid emission angles, except that subjects were unable to discriminate between syntheses using generic-LFOs and no-LFOs, or between recordings and no-LFO. These results are contrary to expectations and may be due to the high degree of similarity between the test signals at the forward and mid emission angles. Future work will continue efforts to validate synthesis methods within the context of a simulated flyover, complete with propagation and listener effects. In particular, a subject's ability to discriminate between syntheses using generic and specific-LFOs in flight is of interest as it can impact the level of sophistication required in the flyover simulation.

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